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## Physical processes in extragalactic radio sources

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# Physical processes in extragalactic radio sources\*

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This paper summarizes extensive observational studies of the closest ultraluminous radio galaxy Cygnus A. These data are used to test jet theory for powering the double-lobed radio emitting structures. Issues addressed include: (i) jet stability, confinement, composition, and velocity, (ii) the double shock structure for the jet terminus and the origin of multiple radio hotspots, (iii) the nature of filamentary structure in the radio lobes, and (iv) the hydrodynamic evolution of the radio lobes within a hot cluster atmosphere. These data are also used to constrain models for relativistic particle acceleration and energy losses (Fermi acceleration and synchrotron aging), as well as to determine magnetic field strengths and morphologies in the radio source and in the surrounding intracluster medium. © 1998 American Institute of Physics. [S1070-664X(98)90805-9]

## I. INTRODUCTION

Normal galaxies are sources of radio continuum emission. The emission is linearly polarized and has a nonthermal spectrum, and the mechanism is thought to be synchrotron radiation emitted by relativistic electrons spiraling in ordered cosmic magnetic fields. These cosmic ray electrons are accelerated in supernova remnant shocks via the first-order Fermi process, hence the radio emission traces the distribution of massive star formation (i.e., blue optical light) in galaxies, blurred somewhat by electron propagation. Typical radio luminosities of normal galaxies are  $10^{39}$  to  $10^{40}$  ergs s<sup>-1</sup>, implying massive star formation rates of one to ten per year.<sup>1</sup>

One of the big surprises in early radio astronomy was the discovery of a class of galaxies with radio continuum luminosities  $\approx 10^{45}$  ergs s<sup>-1</sup>, about  $10^6$  times larger than is typical for normal galaxies. Perhaps more surprising was that the morphology of the radio emission from these galaxies has no resemblance to the parent optical galaxies. The emission occurs in two “radio lobes” extending well beyond the optical dimensions of the galaxies. These hyperactive radio galaxies were the first indication of the quasar phenomenon, in which physical processes beyond normal stellar evolution were releasing energy at an unprecedented rate. The luminosity of these sources are such that they can be detected at very great distances, making them important probes of the high redshift ( $z$ ) universe, and early studies of radio galaxy source counts provided the first evidence that the universe is evolving.<sup>2</sup>

In this paper we review jet theory for powering the double structures in powerful radio galaxies, and we summarize the extensive observations of the archetype powerful ra-

dio galaxy Cygnus A used to test this theory. Cygnus A has played a key role in the field of radio-loud active galaxy research principally because it is by far the closest of the ultraluminous radio galaxies. Figure 1 shows the “Malmquist bias” in the flux limited 3C sample of powerful radio galaxies,<sup>3</sup> i.e., the more luminous sources are at greater distances. The position of Cygnus A on this redshift-luminosity diagram is unique: Cygnus A is about 1.5 orders of magnitude more luminous than any other source at  $z \leq 0.1$ , and most sources with luminosities similar to Cygnus A are located at  $z \geq 1$ .

Since its discovery, Cygnus A has played a fundamental role in the development of jet theory for powering the double structures in powerful radio galaxies. Early aperture synthesis images of Cygnus A led to the discovery of radio “hotspots” at the source extremities.<sup>4</sup> As first pointed out by Hargrave and Ryle,<sup>4</sup> the radiative lifetimes of the relativistic electrons in these hotspots ( $\approx \text{few} \times 10^4$  yr) are less than the light travel time from the nucleus to the hotspot ( $\approx 2 \times 10^5$  yr), hence requiring continuous injection of a population of relativistic electrons at the hot spots. This conclusion led to the “beam” or “jet” model for powering double radio sources.<sup>5,6</sup> The jet model also avoids the dramatic expansion losses inherent in single-burst “plasmon” models for extended structures in radio galaxies.<sup>7</sup> The Cygnus A jet itself was suggested in early Very Long Baseline Interferometry (VLBI) observations of the nucleus,<sup>8</sup> and finally revealed in detail by the first high dynamic range images of the source with the Very Large Array (VLA).<sup>9</sup>

Following are some conventions used in this review. We use  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $q_0 = 0.5$ . Spectral index  $\alpha$  is defined as a function of frequency  $\nu$  and intensity  $I(\nu)$ , as  $I(\nu) \propto \nu^\alpha$ . We use cgs units unless stated otherwise. The symbol  $c$  is used for the speed of light. Some basic physical parameters for Cygnus A are listed in Table I. Some of the

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<sup>†</sup>Invited speaker.

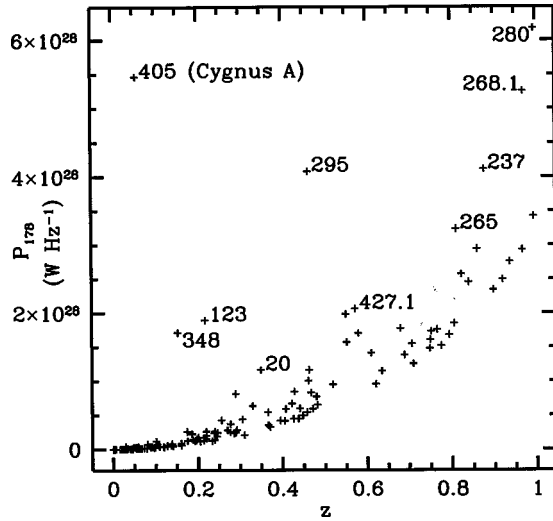


FIG. 1. The radio power-redshift relation for the 3rd Cambridge (3C) sample of  $z < 1$  powerful radio galaxies, i.e., sources with spectral luminosity  $\geq 10^{33}$  ergs  $s^{-1}$  Hz $^{-1}$  at rest frequency 178 MHz (Ref. 3). The more luminous sources are labeled with their 3C number.

material herein is based on the more extensive review by Carilli and Barthel.<sup>10</sup>

## II. JET THEORY

When imaged with adequate sensitivity and resolution, powerful double radio galaxies always show four basic morphological components: at the center of the parent optical galaxy is a compact, typically flat spectrum, high surface brightness “core” component. Extending from this compact component to the source extremities are highly elongated radio emitting structures, or “jets.” The jets usually end at, or point towards, high surface brightness “hot spots” at the extremities of the radio source. The region in between the radio hotspots is filled with extended, low surface brightness emission, known as “radio lobes.” These four components are all evident on the 5 GHz radio image of Cygnus A made



FIG. 2. A greyscale representation of the image of Cygnus A at 5 GHz with 0.4 in. resolution made with the Very Large Array in Socorro, NM. The full source extent is 120 arc sec = 120 kpc. North is at the top and west is to the right.

with the VLA (Fig. 2). The standard physical model explaining and relating these four morphological structures is known as the “jet model” for powerful radio galaxies.<sup>11</sup>

The radio core corresponds to the “central engine,” the ultimate source of energy responsible for the double radio structures. Unfortunately, our understanding of the physics of central engines in active galactic nuclei (AGN) remains limited. Most models for energy generation in AGN involve accretion onto a massive black hole at the center of the parent galaxy. Spectacular confirming evidence for a very centrally condensed mass with an associated disk in a radio loud AGN has come from recent VLBI observations of water maser emission from the nucleus of the galaxy NGC 4258 by Miyoshi *et al.*<sup>12</sup> They show that the masers form a Keplerian rotating disk, with a mass of  $3.6 \times 10^7 M_{\odot}$  within  $0.13 \text{ pc} = 4 \times 10^{17} \text{ cm} = 0.43 \text{ ly}$ , of the galaxy center. We refer readers to Ref. 10 for a review of models for the central engines and jet origin in powerful radio galaxies.

The one certain fact about central engines is that they generate a tremendous amount of energy ( $> 10^{45}$  ergs  $s^{-1}$ ) in a very small volume ( $< 1 \text{ pc}$ ). Some of this energy can be released in the form of highly collimated, relativistic outflows of plasma and magnetic field, the radio “jets.”<sup>13,14</sup> The jets in powerful radio galaxies propagate relatively unhindered until they terminate in a strong shock on impact with the external medium. At this point the jets convert some of their bulk kinetic energy into relativistic particles (through first-order Fermi acceleration), and magnetic fields (through shock compression or turbulent dynamo processes). This post-jet shock fluid emits copious radio synchrotron radiation resulting in the high surface brightness radio “hotspots.”<sup>15</sup> The notion of synchrotron radiation is based on the observed high fractional linear polarizations and nonthermal spectra. The high-pressure shocked jet material then expands out of the hotspot inflating a synchrotron emitting “cavity” in the ambient medium of waste-jet material, the radio “lobe.”

The outline above applies to the radio emitting structures. A second aspect of this model is the effect of the radio source on the ambient medium. Figure 3(a) shows a sche-

TABLE I. Physical parameters for Cygnus A.

|  |   |
|--|---|
| Redshift ( $z$ )                       | 0.0562                                    |
| Luminosity distance                    | 230 Mpc                                   |
| Source size                            | 120 kpc                                   |
| Radio luminosity (10 MHz–400 GHz)      | $9 \times 10^{44}$ ergs $s^{-1}$          |
| Optical galaxy luminosity              | $9 \times 10^{44}$ ergs $s^{-1}$          |
| X-ray luminosity (2–10 keV)            | $1.2 \times 10^{45}$ ergs $s^{-1}$        |
| Internal thermal particle density      | $< 10^{-4} \text{ cm}^{-3}$               |
| External thermal particle density      | $10^{-2} \text{ cm}^{-3}$                 |
| Internal pressure                      | $10^{-8} - 10^{-10} \text{ dyne cm}^{-2}$ |
| External pressure                      | $10^{-10} \text{ dyne cm}^{-2}$           |
| Internal thermal particle temperature  | $> 10^{10} \text{ K}$                     |
| External thermal particle temperature  | $10^8 \text{ K}$                          |
| Internal magnetic field                | 50–300 $\mu\text{G}$                      |
| External magnetic field                | 5 $\mu\text{G}$                           |
| Jet velocity                           | 0.4–1 $c$                                 |
| Jet angle wrt our light of sight       | $40^\circ - 80^\circ$                     |
| Ram pressure advance speed (hot spots) | 0.03 $c$                                  |
| Age of the radio source                | $10^7 \text{ yr}$                         |
| Total energy stored in the radio lobes | $> 10^{59} \text{ ergs}$                  |

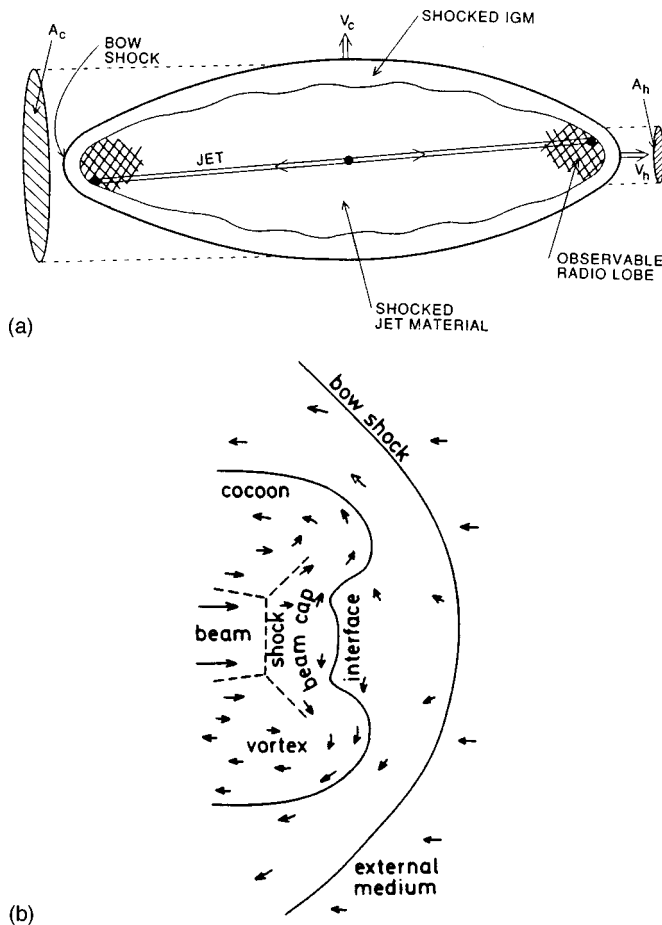


FIG. 3. A schematic representation showing the effect an expanding radio source will have on the external medium. (a) is reproduced from Begelman and Cioffi (Ref. 63), and shows the expected large-scale distribution of shocked ambient gas enveloping the radio lobes. (b) is reproduced from Smith *et al.* (Ref. 64) and shows a detail of the expected double-shock structure at the jet terminus. The interface is the contact discontinuity between shocked jet material and shocked intracluster material (ICM). The beam shock and cap correspond to the radio hotspots, and the cocoon corresponds to the radio lobe.

matic of the effect an expanding radio source will have on the ambient medium on large scales, while Fig. 3(b) shows a detail of the terminal jet shock structure. At the jet terminus two shocks are formed: the jet shock, or Mach-disk, which effectively stops the incoming jet, and the standoff, or bow, shock which acts to accelerate and heat the ambient medium. The two shocked fluids (jet and ambient) meet in pressure balance along a contact discontinuity. Observational evidence suggests that the contact discontinuity is largely stable to mixing (Sec. IV). The overall picture is one of a radio source being enveloped by a “sheath” of shocked ambient medium.

Significant insight into the physics of extragalactic radio sources has come through numerical simulations.<sup>16,17</sup> The basic structure of supersonic jets, hotspots, and radio lobes were delineated in the early work of Norman *et al.*,<sup>18</sup> using two-dimensional, axisymmetric hydrodynamic simulations. A fundamental conclusion from these simulations was that well-developed radio lobes, with widths much larger than the jet width, only result from very underdense jets ( $\eta$

= jet density/external density  $< 0.1$ ), with high internal Mach numbers ( $M > 6$ ). In this case the advance speed of the terminal Mach disk is much less than the jet speed thereby requiring a “waste-bin” for the shocked jet material, i.e., the radio lobe. The beam stability is greatly enhanced by the development of this low-density cocoon within which the jet is overdense, and hence essentially ballistic.<sup>19</sup>

Three-dimensional (3-D) simulations have answered the interesting issue of multiple hotspots in powerful radio galaxies by allowing for jets which alter direction on time scales shorter than the radio source lifetime,<sup>20,21</sup> lending credence to the simple “dentist drill” idea of Scheuer.<sup>22</sup> Simulations including dynamically passive magnetic fields result in total and polarized intensity distributions which match the observations reasonably well, including disk-like structures at the terminal jet shocks, high fractional polarizations along source edges, and filamentary structures in radio lobes.<sup>17,23</sup> Simulations involving dynamically important fields result in a prominent “nose-cone” of emission beyond the terminal Mach disk, and no development of a radio cocoon.<sup>17</sup> Neither of these features is consistent with the observed structures in sources such as Cygnus A. Overall, Clarke<sup>17</sup> concludes that most of the structures of powerful radio galaxies can be explained reasonably within the context of 3-D simulations of light, fast jets which alter direction by small angles on fairly short time scales, and within which the magnetic fields are not dynamically dominant.

### III. THE JETS IN CYGNUS A FROM pc TO kpc SCALES

Jets and related structures in extragalactic radio sources are the largest physically connected structures in the universe, obtaining sizes of order 1 Mpc in some cases.<sup>24</sup> The remarkable collimation and stability of these jets remains somewhat of a mystery and a marvel.<sup>19,25</sup>

A composite of images showing the Cygnus A jets at various scales is shown in Fig. 4. The jet is well collimated and directed, starting on scales  $\leq 0.6$  pc, and continuing to 60 kpc. The kpc-scale jet is composed of a series of elongated knots, oriented at an oblique angle of about  $7^\circ$  to the jet axis. There have been many explanations proposed for knots in jets in powerful radio galaxies,<sup>26</sup> including internal shocks due to surface instabilities, bow shocks due to collisions with small, dense clouds, and jets that have evolved to a “force-free” magnetic field configuration.<sup>27</sup> If the knots are oblique shocks at the Mach angle, then  $\gamma_j M_j = 8$ , where  $M_j$  = jet Mach number, and  $\gamma_j$  = jet Lorentz factor.

Hardee and Clarke<sup>28</sup> present 3-D magnetohydrodynamic (MHD) simulations of a supermagnetosonic jet, driven with small amplitude precession at the origin (to break axisymmetry). Their jet develops twisted filamentary surface structures due to higher-order (“fluting” mode) Kelvin–Helmholtz surface instabilities, and an elliptical distortion in the jet cross section, culminating in a helical bifurcation of the flow. They find that the jet can maintain the distortion over a distance  $\geq 60$  jet radii without disrupting. The predicted radio morphology includes a series of oblique filaments crossing the jet at regular intervals, much like that

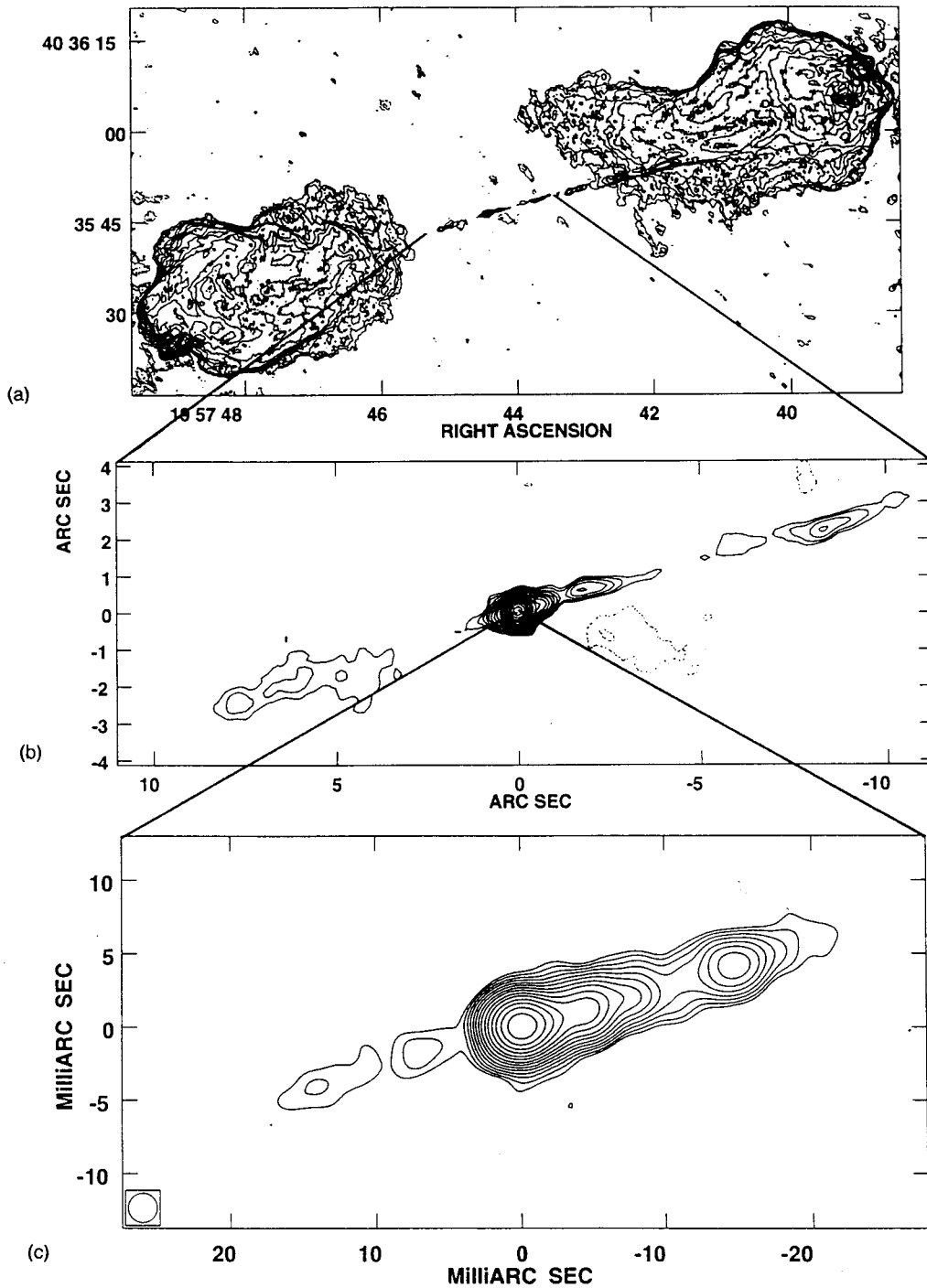


FIG. 4. Contour images of the Cygnus A radio jet on various scales, reproduced from Carilli *et al.* (Ref. 65). The top image shows the kpc-scale radio source at 5 GHz with a resolution of 0.4 arc sec. The contour levels are a geometric progression in  $\sqrt{2}$ , which implies a factor of 2 rise in surface brightness every two contours. The middle image is of the inner kpc-scale jet of Cygnus A with the same contouring as above. The bottom image shows the pc-scale jet of Cygnus A at 3mas resolution (FWHM).

seen for the Cygnus A jet. A detailed comparison between this simulation and the observed structures of the Cygnus A jet by Hardee<sup>29</sup> yields:  $\gamma M_j \approx 10$  and  $\gamma^2 \eta_j \approx 6$ , where  $\gamma_j$  is the jet Lorentz factor,  $\eta_j$  is now the density ratio between the jet and the radio lobe, and  $M_j$  is the jet magneto-sonic Mach number.

Carilli and Barthel<sup>10</sup> present a model in which the jets in Cygnus A are external pressure-confined on pc and kpc scales with a free-expansion zone in between. The pc-scale

jet is underdense relative to its environments, and hence stability becomes a concern. Beyond  $\approx 10$  kpc from the nucleus the jet would be overdense relative to the confining medium (the radio lobes), leading to the relatively stable situation of a supersonic, pressure matched, ballistic jet from  $\approx 10$  kpc to the hotspots. The single requirement of this model is that the lobes be overpressured relative to minimum energy, an assumption that agrees with other observational aspects of the Cygnus A galaxy, as discussed below.

Sorathia *et al.*<sup>30</sup> use three epochs of VLBI observations to determine the apparent velocity of one component in the pc-scale jet to be  $0.4 \pm 0.1 \times c$ . They find a value for the ratio of the integrated flux density in the jet to that in the counterjet of  $5 \pm 2$  at 5 GHz. Using these two parameters, they apply the equations for the symmetric twin relativistic jet model<sup>31</sup> to constrain the jet angle relative to our line of sight  $\theta$  and to constrain the true jet velocity. The values are listed in Table I. In this model, the relative brightness of the jet and counterjet is set simply by relativistic boosting. According to this model, the jet in Cygnus A must be at an intermediate angle relative to our line of sight, and moving at a mildly relativistic velocity. Higher resolution observations of Krichbaum *et al.*<sup>32</sup> show that the jet components may have a range in apparent velocities (between 0.2 and  $0.8 h^{-1}$ ). Such an observation suggests that the apparent velocities represent a pattern speed, e.g., of surface waves on the jet, and not the true jet fluid velocity. If so, this would invalidate the standard analysis above.

Estimates of the velocity of the jet on kpc scales are even more problematic, but there are a few indirect methods that have been used. One method is to consider the rate of bulk kinetic energy supplied by the jet, and the jet thrust. This calculation leads to  $v_j \geq 0.1c$ .<sup>10</sup> Muxlow *et al.*<sup>33</sup> and Carilli *et al.*<sup>34</sup> have used the observed spectra of the Cygnus A radio hotspots to constrain various physical parameters of the jet. They conclude that the various “features” in the hotspot spectra are consistent with a model involving particle acceleration at a strong shock in a Newtonian fluid with a mildly relativistic jet velocity ( $\approx 0.4c$ ).

#### IV. THE HOTSPOTS AND RADIO LOBES

High-resolution images of the hotspot regions in Cygnus A can be found in Refs. 35, 36, and 10. Cygnus A shows two hotspots in each lobe. Such multiple hotspots are common in powerful radio galaxies.<sup>37</sup> The generally accepted model for multiple hotspots is the “dentist drill” model, in which jets alter direction on time scales shorter than the time scale it would take for an “abandoned” hotspot to fade to the background surface brightness level due to expansion losses ( $\approx 10^5$  yr).<sup>22</sup> In this model the more compact hotspot represents the newest hotspot where the jet impinges obliquely on the side wall of the radio lobe, extending and widening the lobe in this new direction. The secondary hotspot could be explained by one of two models: collimated outflow from the primary, or “dying hotspots,” i.e., the location of previous jet termination.<sup>20,38</sup> Both of these solutions have significant uncertainties.<sup>21</sup>

Another point that is relevant in the interpretation of the shock structures at the jet terminus in Cygnus A is the bow shock discovered in the rotation measure distribution.<sup>39</sup> The bow shock is seen as an “arc” of discontinuous change in rotation measure (RM) roughly concentric with the primary hotspot, with a standoff distance of about 3 in. This jump in RM signals the point at which the thermal particles and tangential magnetic fields in the intercluster medium (ICM) are compressed by the shock due to the supersonic advance of the primary hotspot. Detecting this radio quiet bow shock

confirms the basic double-shock structure for the jet terminus in powerful radio galaxies, and implies that the contact discontinuity is stable to mixing.

The lobes in Cygnus A show filamentary structures, a common feature in extragalactic radio sources (Fig. 2). Many explanations have been considered for filaments in radio sources, including cooling instabilities,<sup>40</sup> regions of anomalous resistive reconnection,<sup>40,41</sup> and turbulent vortices in back flow in the radio lobe.<sup>18</sup> The 3-D simulations including passive magnetic fields of Clarke<sup>17</sup> show the natural development of rope-like filaments in radio lobes corresponding to regions of enhanced magnetic field. The intermittent “bundles” field occurs in regions of large velocity shear implying a simple kinematic dynamo process as the origin for the enhanced field regions. The polarization characteristics of these filaments are consistent with that observed for Cygnus A (high fractional polarization with longitudinal fields; Sec. VI).

#### V. RADIO CONTINUUM SPECTROSCOPY

The hotspots in Cygnus A have spectral indices of  $-0.5$  between 1.5 GHz and 5 GHz, with gradual steepening of the spectra to indices less than  $-2$  in the tails of the radio lobes (Fig. 5). This spectral steepening inward from the hotspots is characteristic of powerful radio galaxies in general. This effect has been explained as synchrotron radiative “aging” of the relativistic electrons. Synchrotron radiation preferentially depletes the highest energy electrons, leading to a steepening in the emission spectrum at high frequencies over time.<sup>42</sup> The inference is that the electrons at the center of the source are “older” than those closer to the hotspots, i.e., that the source is expanding in time with the principal site of particle acceleration being the hotspots, in agreement with the jet model. The connection between radio spectrum and age allows for a study of the growth and evolution of the lobes by careful measurement of the spectrum throughout the length and width of the source. Spectral aging studies also allow for the study of the microphysical processes in the relativistic electrons by determining the behavior of the spectrum at frequencies higher than the break frequency.<sup>43,44,34</sup>

The integrated spectra of the hotspots in Cygnus A at 4.5 arc sec resolution are shown in Carilli *et al.*<sup>34</sup> These spectra are well fit by a continuous injection (CI) model spectrum, in which a power-law distribution of particles is continuously injected at the hotspot. The low-frequency spectral index, or injection index, is  $-0.5$  for the hotspots, as predicted by diffusive shock acceleration theory for a nonradiative, strong shock in a monatomic Newtonian fluid.<sup>45,46</sup> However, the effects on injection index assuming a relativistic jet velocity, or allowing for modification of shock structure due to upstream high-energy particles, are minor,  $\pm 0.1$  or so in spectral index, and certainly cannot be ruled out.<sup>47</sup> At frequencies above about 10 GHz the hotspot spectra steepen to an index of  $-1$ , as predicted by the CI model. The “break frequency” of 10 GHz implies a spectral age  $\approx 10^5$  yr using minimum energy fields. Using this age and the size of the hotspot regions then leads to an out-flow velocity of  $0.08 \times c$ .<sup>34</sup>

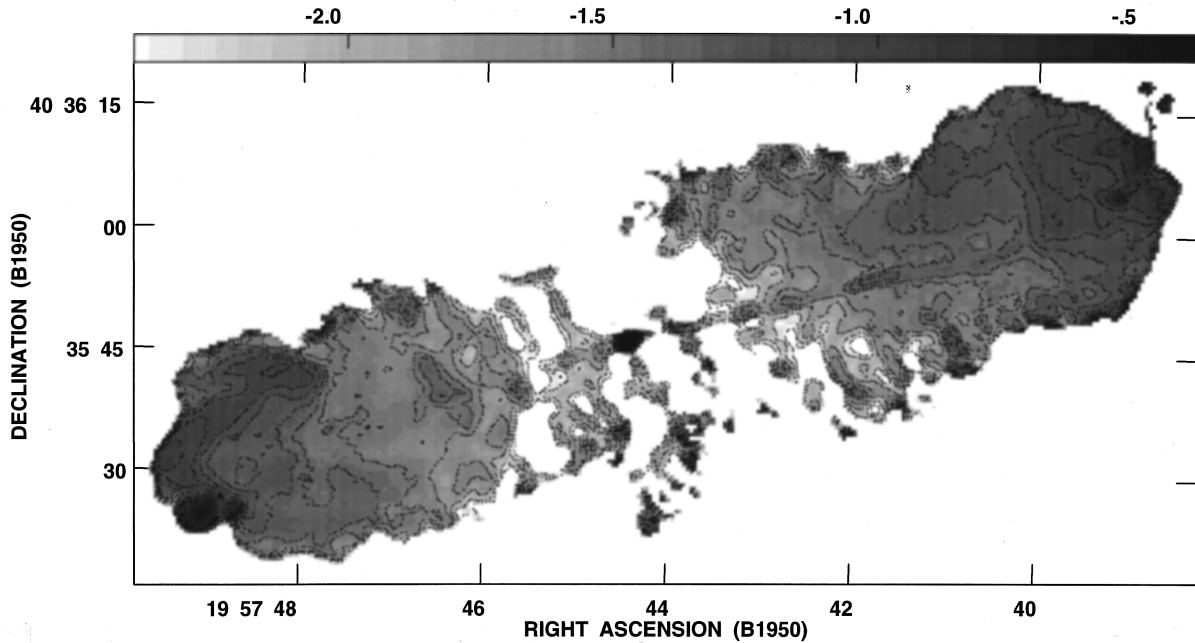


FIG. 5. The spectral index distribution across Cygnus A between 1.5 and 5 GHz at 1.1 arc sec resolution. The greyscale ranges from  $-2.4$  (white) to  $-0.4$  (black), and the contour levels are  $-2.5, -2.3, -1.9, -1.7, -1.5, -1.4, -1.3, -1.2, -1.1, -1.0, -0.9, -0.8, -0.7, -0.5$ .

Spectral aging along the radio lobes of Cygnus A has been considered in detail by Carilli *et al.*<sup>34</sup> They find a roughly linear increase in age with distance from the hotspots. The implied “separation velocity” is  $0.06c$ , derived using minimum energy fields of  $50 \mu\text{G}$  (Sec. VI). The oldest electron populations are found in the radio “plumes” extending to the north and south of the center of the radio bridge, with an implied source age of 6 Myr. Note that the separation velocity is the sum of two velocities: the source advance speed and the back-flow velocity of material in the lobes. In an attempt to balance the separation velocity against the ram pressure advance speed, Carilli *et al.*<sup>34</sup> proposed a self-consistent, although admittedly *ad hoc*, model in which the fields are systematically below minimum energy values by a factor of 3 resulting in an average source advance speed  $\approx$  separation velocity  $\approx 0.01c$ , and a source age of 30 Myr.

In terms of the shape of the spectra above the break, Carilli *et al.*<sup>34</sup> find that the lobe spectra steepen more than allowed by continuous injection models, but less steeply than exponential. The best fitting model involves “one-shot” injection with subsequent radiative losses, but without continuous isotropization of the pitch-angle distribution which would lead to an exponential cutoff.<sup>42–44</sup> This is hard to justify physically since pitch-angle scattering of streaming electrons by self-induced Alfvén waves is thought to be an efficient process.<sup>47</sup> A possible solution to this is to allow for a distribution in magnetic field strengths.<sup>48</sup> Last, Carilli *et al.*<sup>34</sup> determine an injection index of  $-0.7$  in the radio lobes, while the best fit value for the hotspots is  $-0.5$ . This “injection index discrepancy” is difficult to reconcile with the idea that the principal location of particle acceleration is the hotspot.

Given these problems, Rudnick and Katz-Stone<sup>49</sup> have reanalyzed the spectral data for Cygnus A and have raised some disconcerting questions. First, they question the existence of a power law in any region of the spectrum. And second, they find that all spectra in the source can be explained by simply shifting (in the log plane) a single continuous function. They argue for a “universal spectrum,” with “no evidence for evolution of the electron energy distribution,” other than this simple scaling in frequency and intensity. We refer the reader to the above reference for more information on this alternative interpretation.

## VI. MAGNETIC FIELDS

Most studies of cosmic radio sources use the “minimum energy” assumption to estimate field strengths. The minimum energy calculation<sup>50</sup> relies on the fact that given a synchrotron emissivity, the summed energy density in relativistic particles and magnetic fields can be minimized by adjusting the magnetic field strength. The minimum energy condition implies rough equipartition of energy between fields and relativistic particles. The minimum energy calculation involves a number of assumptions, as outlined in Miley.<sup>51</sup> The minimum energy fields in the hotspots in Cygnus A are about  $300 \mu\text{G}$ , while those in the lobes are about  $50 \mu\text{G}$ , and those in the jets are  $100 \mu\text{G}$ . The corresponding minimum pressures are  $3 \times 10^{-9}$ ,  $8 \times 10^{-11}$ , and  $3 \times 10^{-10} \text{ dyn cm}^{-2}$ , respectively.

The question of the validity of the minimum energy assumption is an important one.<sup>52</sup> One observation that supports the minimum energy assumption is the detection of x-ray emission from the hotspots of Cygnus A (see Fig. 7 below). Harris *et al.*<sup>53</sup> show that the x-ray emission can be



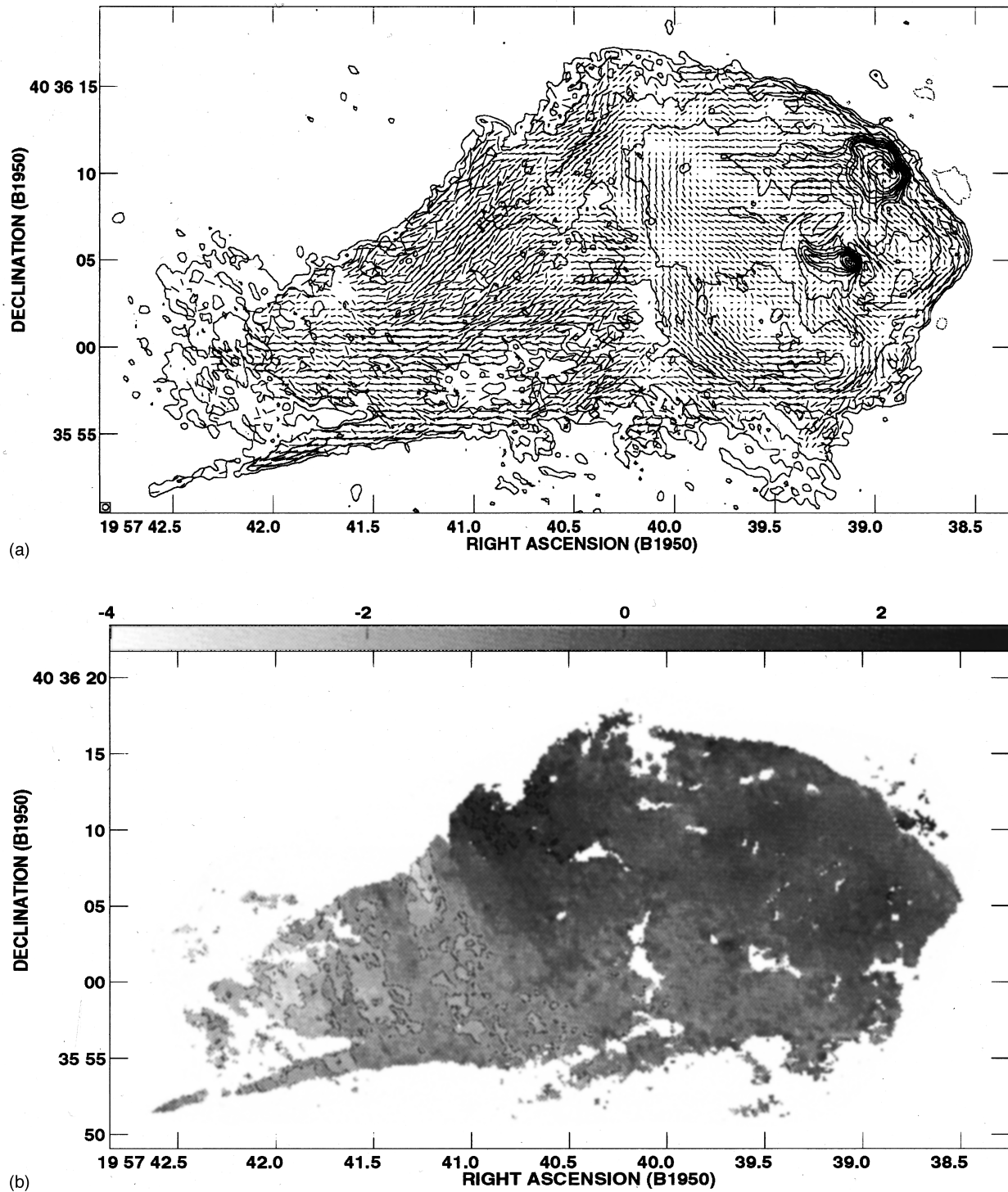


FIG. 6. (a) The contours are of total intensity from Cygnus A at 8 GHz, 0.35 arc sec resolution. The vectors show the projected magnetic field distribution across the source. The length of the vectors indicate the fractional polarization, with 1 in. = 77%. (b) The Faraday rotation measure distribution across the northwestern radio lobe of Cygnus A. The greyscale ranges from  $-4000$  (white) to  $3000 \text{ rad m}^{-2}$  (black).

explained by synchrotron self-Compton (SSC) radiation, i.e., up-scattering by the relativistic electrons of their own synchrotron radio photons. The combination of SSC emissivity and synchrotron emissivity allows for the derivation of the magnetic field independent of minimum energy assumptions. Harris *et al.*<sup>53</sup> calculate magnetic field strengths of  $\approx 200 \mu\text{G}$  for the hotspot regions, close to the minimum energy value.

Multifrequency radio continuum polarimetric imaging determines both the fractional linear polarization and the projected magnetic field structure in the radio source. Figure 6 shows the fractional polarization and projected magnetic field distribution across the northwest radio lobe of Cygnus A. The emission is substantially polarized, reaching as high as 70% in some regions, the theoretical maximum for opti-

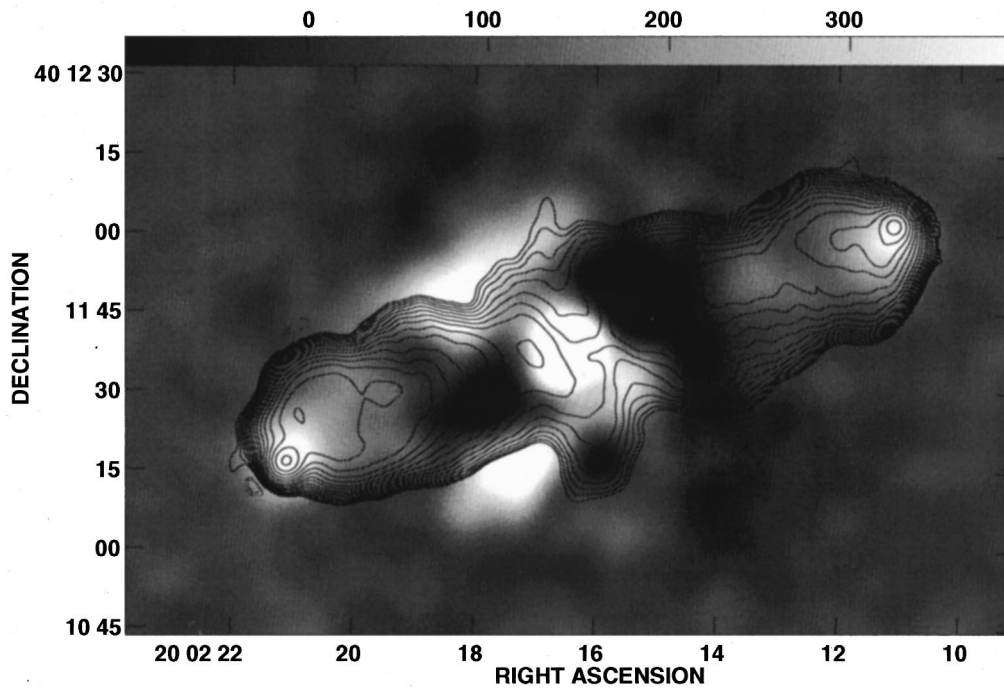


FIG. 7. The contours show a radio image of Cygnus A at 327 MHz with 5 in. resolution made with the VLA. The greyscale is from an x-ray observation of Cygnus A, reproduced from Carilli *et al.* (Ref. 62). The smooth cluster emission has been subtracted in order to show the effects of the radio source on the x-ray morphology. White corresponds to an excess of emission, while black corresponds to a deficit of emission. Nonthermal (synchrotron self-Compton) x-ray emission from the radio hotspots is visible on this plot, as is evidence for the hydrodynamic interaction of the radio lobes with the cluster gas (deficits at the tails of the lobes, and excesses along some edges of the lobes).

cally thin synchrotron emission from a population of relativistic electrons with a power-law energy distribution and an isotropic pitch angle distribution in a uniform magnetic field.<sup>42</sup> An important point is that high fractional polarizations are seen on fairly large scales in the tails of the radio lobes. The implication is very well ordered fields on scales of 10 kpc. The projected fields generally follow parallel to the edges of the source, to the bright ridges in the hotspots, and to the filamentary structure in the lobes. The field projects along the length of the jet and along the tails of the radio lobes.

Laing<sup>54</sup> presents an analytic model for magnetic fields in radio galaxies involving simple kinematic dynamo processes in the radio source, i.e., shear and/or compression by turbulent fluid motions of a magnetic field which is “frozen-in” to the fluid due to the very high conductivity of a collisionless plasma. These processes can result in regions of highly anisotropically tangled field where one dimension of the turbulence is “reorganized” by compression or shear. In certain projections this can result in observed fractional polarizations approaching the theoretical maximum. The implication is that the fields do not dominate the dynamics in the radio source.

## VII. THE FARADAY SCREEN: MAGNETIC FIELDS IN CLUSTER GAS

One of the most interesting, and surprising, results from the study of the polarized emission from Cygnus A was the discovery of extremely large values of Faraday rotation by

Dreher *et al.*<sup>55</sup> These authors find that Cygnus A lies behind a deep “Faraday screen,” with rotation measures varying from  $-4000$  to  $3000 \text{ rad m}^{-2}$  across the source [Fig. 6(b)]. In general the distribution is not random, but displays structure with coherence over spatial scales of order 10 kpc. Perhaps most importantly, Dreher *et al.*<sup>55</sup> find that the total rotation of the position angle of the polarization vector exceeds  $600^\circ$  in many regions, without departure from a  $\lambda^2$  dependence, where  $\lambda$  = observed wavelength, and without depolarization, providing mathematically rigorous proof that the Faraday rotation cannot be internal to the source but must be by an external, magnetoionic screen.<sup>56</sup>

Dreher *et al.*<sup>55</sup> propose that the origin of the large RM’s is in the hot intracluster gas in which Cygnus A is embedded (Sec. VIII). The implication is that the large-scale cluster gas is substantially magnetized, with magnetic field strengths between 2 and  $10 \mu\text{G}$ , depending on geometry. Also, from the lack of wavelength-dependent fractional polarization at fixed resolution, Dreher *et al.*<sup>55</sup> derive an upper limit to the thermal electron density in the radio lobes of  $2 \times 10^{-4} \text{ cm}^{-3}$ , again depending on geometry.

The detection of extreme rotation measures towards Cygnus A has been followed by similar detections in other radio galaxies at the centers of dense x-ray cluster atmospheres,<sup>57,58</sup> implying that thermal cluster atmospheres must be substantially magnetized, with fields of order of a few  $\mu\text{G}$ . In most cases the pressure in the intracluster fields is below the thermal energy density, implying a minor dynamical role for the fields. Even dynamically unimportant

fields alter substantially the thermal conductivity of the plasma, and hence are very important when considering the cooling and heating of the ICM (Rosner, this volume).

### VIII. THE X-RAY CLUSTER: INTERACTION WITH THE RADIO SOURCE

The Cygnus A radio source is located at the center of a dense, hot, thermal x-ray emitting cluster atmosphere. This atmosphere extends at least 500 kpc from the cluster center. Reynolds and Fabian<sup>59</sup> derive a thermal gas density of  $0.008 \text{ cm}^{-3}$  at the hotspot radius, a temperature of  $10^8 \text{ K}$ , a total gas mass of  $4 \times 10^{13} M_{\odot}$ , and a total gravitational mass of  $3 \times 10^{14} M_{\odot}$ . Cygnus A provides the opportunity to study the interaction between the radio source and the ICM in unprecedented detail. The x-ray image of Cygnus A is shown in Fig. 7 after subtraction of the smooth cluster emission. This image reveals the presence of the radio source within the cluster: excess x-ray emission from the hotspot regions, most of which is probably nonthermal (Sec. VI), deficits of x-ray surface brightness in the regions coincident with the inner parts of the radio lobes, and knots of excess x-ray emission along some of the edges of the radio source.

Clarke et al.<sup>60</sup> present results from a 3-D numerical simulation of the expected x-ray surface brightness distribution in the centers of clusters containing supersonically expanding radio sources such as Cygnus A. They show that the general anticorrelation between x-ray and radio surface brightness in Cygnus A within 35 arc sec of the nucleus is consistent with the jet model. The deficits correspond to regions evacuated by the radio lobes, while the excesses correspond to emission from gas which has been displaced by the radio source. From the depth of the "holes" in the x-ray gas at the positions of the radio lobes, they conclude that the radio source must effectively exclude the ICM, again implying a contact discontinuity that is stable to mixing.

An important question is pressure balance of the various gaseous components in the cluster center. At the hotspot radius the pressure in the unperturbed ICM is  $1 \times 10^{-10} \text{ dyn cm}^{-2}$ . Hence the hotspots are highly overpressured relative to the external medium, and must be ram pressure confined, with a required external Mach number 6. Within 20 arc sec of the cluster center the gas pressure has risen to  $\geq 5 \times 10^{-10} \text{ dyn cm}^{-2}$ .<sup>59</sup> This is comparable to the pressure in the clumpy optical line emitting gas seen on kpc scales,<sup>61</sup> and to the minimum energy pressure in the kpc-scale radio jet. However, the minimum pressure in the radio lobes is a well below the x-ray gas in these regions. Hence the lobes within 15 kpc of the cluster center appear underpressured relative to the thermal gas, a statement in conflict with the observed exclusion of the ICM from the radio lobes. Carilli et al.<sup>62</sup> discuss two possible solutions to this dilemma: either a significant departure from minimum pressure conditions in the radio lobes, or lobe pressures dominated by relativistic protons. As pointed out above, such a departure from minimum energy conditions in the lobes could also solve the jet confinement problem.

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